Dredging of Drainage Ditches Increases Short-Term Transport of Soluble Phosphorus

Douglas R. Smith,* E. A. Warnemuende, B. E. Haggard, and C. Huang

ABSTRACT

Managed drainage ditches are common in the midwestern United States. These ditches are designed to remove water from fields as quickly as possible, and sediment buildup necessitates dredging, to ensure adequate water removal. This laboratory study was conducted to determine the impact of ditch dredging on soluble phosphorus (P) transport. Ditch sediments were collected from a drainage ditch in northeastern Indiana immediately before and after dredging. The sediments were placed in a stream simulator, and stream water was loaded with 0.55 mM P for 5 d (adsorption experiment). Water was then removed, and "clean" water (no P added) was used for a desorption experiment, lasting 1 d. During the adsorption experiment, pre-dredged sediments were able to remove P from the water column quicker, and P concentrations 120 h after introduction of high P water were lower for the pre-dredged sediments (0.075 mM P) than the dredged sediments (0.111 mM P). During the desorption experiment, P was released to the water column slower in the pre-dredged treatment than the dredged treatment (instantaneous flux at $t = 0$ was 0.205 μM P h^{-1} for pre-dredged and 0.488 μM P h^{-1} for dredged). This occurred despite higher Mehlich 3–extractable P in the pre-dredged sediments than the dredged sediments. Equilibrium phosphorus concentrations (EPC$_o$) were lower in the pre-dredged sediments during both adsorption and desorption experiments. Transport of soluble P immediately after dredging will likely increase in drainage ditches; however, dredging is a necessary management tool to ensure adequate discharge of water from surrounding fields.

ALGAL PRODUCTION in many U.S. surface waters is limited by phosphorus (P) concentrations, and thus small inputs of bioavailable P from anthropogenic sources can result in accelerated eutrophication (Schindler, 1977). Agriculture has been identified by the USEPA as one of the primary contributors of nonpoint-source P to surface water (USEPA, 1990).

A large amount of research has been conducted on ways to decrease or eliminate P discharges from agricultural lands. Efforts to decrease P losses at the field scale have included treatment of manures with chemicals (Shreve et al., 1995; Smith et al., 2004a), modification of animal diets (Smith et al., 2004a, 2004b; Maguire et al., 2003, 2004), and treatment of soils with wastewater treatment residuals (Rhoton and Bigham, 2005). Recent research has been used to identify sites vulnerable to P losses and has placed restrictions on application of manure or fertilizers to those sites based on risk assessment tools collectively known as the P index (Sharpley et al., 2003; DeLaune et al., 2004). Despite these efforts, sufficient P is still discharged to surface waters to induce anthropogenically accelerated eutrophication (Schindler, 1977; Carpenter et al., 1998).

Once P reaches surface water, the P in the water column interacts with sediments, such that the sediments can be a source or sink for water column P. Haggard et al. (2004) found that point sources were still important contributors to P in streams, and that chemical amendments could increase P buffering capacity and decrease readily exchangeable P in the sediments. Chemical treatments also changed the physiochemistry of the sediments such that they were a stronger sink of P in the water column than untreated sediment (Haggard et al., 2004; Smith et al., 2005).

Runoff from soils fertilized with poultry or dairy manure can increase stream P concentrations, and increase labile P and equilibrium phosphorus concentrations (EPC$_o$) of sediments (McDowell and Sharpley, 2003). In laboratory experiments using simulated streams, the dissolved P in the water column was related to the EPC$_o$ of sediments taken from several sites in a central Pennsylvania stream (McDowell and Sharpley, 2003).

When sediment samples were collected from seven sites in three tile-fed drainage ditches in northeastern Indiana, sediments from four sites acted as sinks for P in the water column, and sediments in the remaining three sites acted as sources of P to the water column (Smith et al., 2005). The most significant change in sediment dynamics between sites within a single ditch was observed where a confined animal feeding operation (CAFO) was located between the two sites. Sediment samples collected above the CAFO acted as a P sink, while the sediments below the CAFO were contributing P to the water column. When aluminum sulfate and calcium carbonate chemical treatments were applied to the sediments, all sites shifted to P sinks in the water column (Smith et al., 2005). Chemical treatment has been shown to be effective in lakes and reservoirs (Welch and Schrieve, 1994; Kopacek et al., 2000; Haggard et al., 2005); however, this technology has not been extensively tested in streams or ditches to determine the longevity of in situ efficacy.

Dredging is a common practice to remove sediments from ditches, streams, rivers, or estuaries, and is generally performed to optimize the flow of water or to ensure adequate water depth for boats or ships, or is an artifact of shell fish harvests. Field experiments involving dosing of streams with high levels of P indicated that sediments were able to remove P from the water column

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Abbreviations: EPC$_o$, equilibrium phosphorus concentration; PSR, phosphorus sorption ratio.

(Macrae et al., 2003). Dosing occurred in early summer and early fall, and one of three streams was dredged between dosings, with no obvious impact on P removal by sediment (Macrae et al., 2003). In a suburban watershed, fluxes of P from a dredged stream sediment were lower; however, this may have been due to the removal of labile P fractions in the benthic sediments before dredging (Xuefeng et al., 2002). Recently, dredging of reservoirs has been suggested as a method to remove P rich sediments, thereby decreasing the rate of eutrophication, however detailed analysis of P fluxes from sediments indicated that this would only be a temporary solution to eutrophication problems (Kleeberg and Kohl, 1999), and would also be prohibitively expensive.

The physiochemistry governing the source–sink relationship between stream sediments and water column P concentrations is dynamic and can be affected by chemical treatments; the impacts of physical treatments on the physiochemistry of P dynamics immediately following treatment have not been well documented. The objectives of this study were to determine how physical removal of sediments by dredging impacts the interactions of P at the sediment–water interface and the potential delivery of soluble P to receiving waters.

MATERIALS AND METHODS

Sediment samples were collected from a tile-fed drainage ditch in northeastern Indiana, USA, as the ditch was actively being dredged to remove sediment buildup. The ditch used for this experiment is described as Ditch B by Smith et al. (2005). Briefly, this ditch has a contributing area of approximately 1400 ha, 85% of which is in row crops (primarily corn and soybean), and 12% of which is in grass or pasture production. Primary soils in the contributing area of this ditch are Blount silt loam (fine, illitic, mesic Aeric Epiaqualfs), Pewamo silty clay (fine, mixed, active, mesic Typic Argiaquolls), and Glynwood loam (fine, illitic, mesic Aquic Hapludalfs). Water from this ditch flows into Cedar Creek, which in turn flows into the St. Joseph River, the drinking water source for the city of Ft. Wayne, Indiana, USA. Dredging started at the confluence of the ditch and Cedar Creek, and continued upstream. Before the dredging that occurred during sample collection for this study (December 2004), this ditch was previously dredged in 1996. Dredging removed approximately 30 cm of surface sediments from the bottom of the drainage ditches. The exposed material was representative of the dense, massive structure of the glacial till commonly found at analogous depths from the soil surface (2 to 4 m) in the glacial till soils of northeastern Indiana.

Samples for this study were collected approximately 5 m upstream from the dredging (pre-dredged), and approximately 5 m downstream from the dredging (dredged). Approximately 130 L of sediment was collected from both sites, placed into plastic containers, and transported to the laboratory. Upon arrival at the laboratory, sediment samples were refrigerated at 4°C until laboratory experiments could be performed. Particle size distribution was determined on pre-dredged and dredged sediments using the micropipette method (Miller and Miller, 1987). Loss on ignition (LOI) procedures were used to determine organic matter content of sediments (Nelson and Sommers, 1982).

To study the impacts of dredging on P transport, a fluvarium was used, similar to the one described by McDowell and Sharpley (2003). For this study, the fluvarium used was 8.4 m long with three flumes, which were each 20 cm wide. Approximately 60 L of sediment were packed into a flume to a depth of 3 to 3.5 cm for each stream simulation. Two replications of each ditch sediment were used in this study. Only two flumes were used for this study, so two runs were made, each run using sediments from both pre-dredged and dredged sediments.

Water from each flume was recirculated during the stream simulation, similar to experiments reported by McDowell and Sharpley (2003). The slope of the fluvarium was set to 1% for all simulations, and is equivalent to the slope in the ditch from which sediments were collected. Simulated ditch water was made from deionized water by adjusting to 2.5 mM CaCl$_2$. This concentration was chosen to simulate the ionic strength of water naturally present in the ditch from where these sediments were collected. At the beginning of both replications, the simulated ditch water was adjusted to approximately 0.55 mM P using KH$_2$PO$_4$. Water column P concentrations in these ditches have been observed to be as high as 0.25 mM P. The initial concentration of 0.55 mM P was chosen to evaluate a worst-case scenario, and runoff studies following fertilizer or manure application have shown P concentrations as high as 0.65 mM (Smith et al., 2004b; DeLaune et al., 2004). A flow rate for the water of 10 L min^{-1} was used, as this was sufficient flow for approximately 2 to 3 cm depth of water in the channels, but low enough to induce only laminar flow to the channels, and similar to flow velocities at the time of sediment collection. Laminar flow was essential, so as to not erode sediments during the experiment. During this initial experiment, P rich water was used to study the adsorption of P by the sediments from the water column (hereafter referred to as adsorption experiment). Samples were taken using an automated water sampler (Model 3700; Isco, Lincoln, NE) hourly for the first 24 h, and then every 6 h thereafter, to 120 h. Samples were collected from the autosampler daily for processing. A 60-mL sample was poured off for total P analysis, and a 20-mL subsample was filtered through a 0.45-μm membrane filter.

At the end of the adsorption experiment, water was drained, reservoirs were rinsed, water containing 2.5 mM CaCl$_2$ added, and water flow was restarted at 10 L min^{-1}. No additional P was added to water during this experiment, so that P desorption from the sediments to the water could be examined (hereafter referred to as the desorption experiment). Samples were collected by the autosamplers hourly for 24 h. Samples were processed for the desorption experiment in the same manner as samples from the adsorption experiment.

Dissolved P was analyzed on filtered, acidified samples using inductively coupled argon plasma (ICAP) spectrophotometry (Optima 2000; PerkinElmer, Wellesley, MA). Unfiltered samples were digested using the total Kjeldahl procedures, and analyzed for total P using ICAP spectrophotometry. Since P was added as KH$_2$PO$_4$, soluble P accounted for 97 to 100% of the P in the water column, and only soluble P will be presented in this paper.

For data collected during the adsorption experiment, P concentrations were plotted as a function of time. With P concentration on the y axis, and time as the x axis, P concentrations were fitted to a logarithmic decay function following the formula:

$$C = C_\infty + \alpha\, e^{-\beta t} \qquad [1]$$

where C is the P concentration calculated at time t, C_∞ is the calculated P concentration at $t = \infty$, α is a calculated constant, β is the rate constant, and t is the time in hours.

For data collected during the desorption experiment, P concentrations were also plotted as a function of time. The P

concentrations were then fitted to an exponential increase to a maximum function using the formula:

$$C = C_o + \alpha(1 - e^{-\beta t}) \qquad [2]$$

where C_o is the concentration at $t = 0$. From Eq. [1] and [2], an instantaneous rate of flux at $t = 0$ was calculated by determining the first-order derivative of the equation.

Sediment samples were collected during the adsorption and desorption experiments for chemical analysis. Phosphorus, Al, and Fe were extracted using the Mehlich-3 procedure with a 10:1 extractant to sediment ratio, with the supernatant analyzed with ICAP spectrophotometry (Mehlich, 1984). The phosphorus sorption ratio (PSR) was calculated as mmol P/(mmol Al + mmol Fe) per the procedures of Maguire and Sims (2002).

Phosphorus sorption isotherms were conducted on sediments, with initial P concentrations in solution of 0, 0.016, 0.081, 0.202, 0.323, 0.646, and 1.614 mM P. Following centrifugation at $5800 \times g$ and filtration with a 0.45-μm filter, supernatants were analyzed for P concentration using ICAP spectrophotometry. Equilibrium phosphorus concentrations (EPC$_o$) were calculated by regressing the mass of P adsorbed per kg dry sediments against the initial P concentration in the water used for the P sorption isotherms.

Statistical analysis was performed with paired t tests for kinetics of adsorption and desorption data for sediment and water column P concentrations collected during the fluvarium runs. Correlation coefficients (R^2) were calculated for the regression equations (Eq. [1] and [2]) for P water concentrations. An a priori level of 0.05 was used to determine significant differences. Statistical analysis was performed using JMP Version 5.1 (SAS Institute, 2003).

RESULTS AND DISCUSSION

The surface sediments present before dredging were finer textured than those exposed during the dredging process (Table 1). A decrease in the organic matter content of benthic sediments was observed from about 5% in pre-dredged sediments to 2% following dredging. The exposed sediments following dredging also showed strong redoximorphic features, which may suggest removal of Fe in the sediments exposed by dredging (Ponnamperuma, 1972).

Adsorption Experiment

Relative P concentrations in the water column during the adsorption experiment rapidly decreased from approximately 0.54 mM at time 0 for both pre-dredged and dredged sediments (Fig. 1). Similar observations have been made following the addition of K_2HPO_4 (House et al., 1995) and runoff from manured soils (McDowell and Sharpley, 2003). Throughout the 119 h of measurements, P concentrations in the pre-dredged treatment were less than P concentrations in the dredged treatments ($P < 0.001$). The rate of decrease however was quite different. The pre-dredged sediments appeared
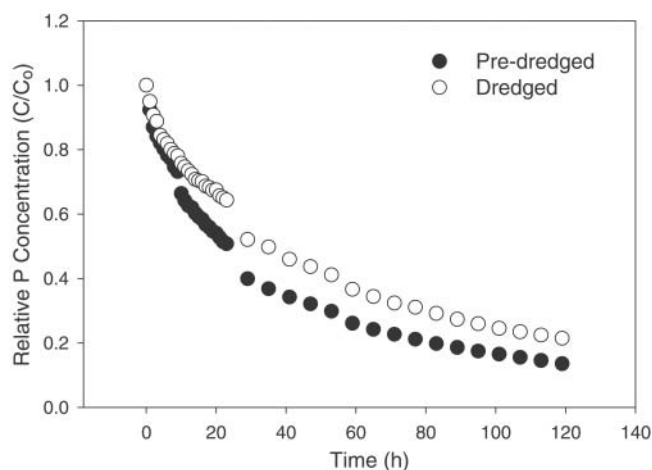

Fig. 1. Relative P concentration in simulated ditch water for pre-dredged and dredged sediment treatments for 119 h following initial P loading in a water column of approximately 0.55 mM P.

to remove P from the water column quicker than the dredged sediments. Lower final water column P concentrations were also observed in the pre-dredge treatment; specifically, water column P concentrations were 0.075 mM for pre-dredged and 0.095 mM for dredged treatments at 119 h ($P < 0.05$).

Decreased water column P concentrations occurred quicker in the pre-dredged sediments despite greater Mehlich-3 P levels compared to dredged sediments ($P = 0.01$; Table 2). The reason for the decrease was most likely due to much lower EPC$_o$ concentrations for these sediments compared to the dredged sediments ($P = 0.05$). In the adsorption experiment, the mean EPC$_o$ for the pre-dredged sediments was −0.009 mM compared to 0.026 mM in the dredged sediments (Table 2). This suggests that pre-dredged sediments could buffer the water column P at much lower P concentrations, despite having greater Mehlich-3 P.

Dredged sediments contained less fine particles and less organic matter than the sediments present before dredging (Table 1). These observations are consistent with the Mehlich-3 and EPC$_o$ results, as the dredged sediments would have less surface area for binding P and removal of P from the water column. Assuming the estimated mean spherical diameters of particles were 0.2, 0.011, and 0.0015 mm for sand, silt, and clay, respectively, the pre-dredged sediments had a specific

Table 1. Particle size distribution and organic matter content of benthic sediments for pre-dredged and dredged sediments.

Treatment	Sand	Silt	Clay	Organic matter
	%			
Pre-dredged	57.9	17.1	20.1	4.9
Dredged	80.4	3.0	14.6	2.0

Table 2. Mehlich-3 P, Al, and Fe concentrations, phosphorus sorption ratio (PSR), and equilibrium phosphorus concentrations (EPC$_o$) for pre-dredged and dredged sediments during the adsorption and desorption experiments using stream simulations.

Treatment	Mehlich-3			PSR	EPC$_o$
	P	Al	Fe		
	mg kg^{-1}				mM
Adsorption					
Pre-dredged	121	313	2180	0.077	−0.0090
Dredged	82	90	1190	0.119	0.0261
Desorption					
Pre-dredged	151	475	2310	0.081	−0.0071
Dredged	118	125	1260	0.150	0.0048

surface area of roughly 9600 cm^2 cm^{-3}, while the specific surface area for the dredged sediments would be approximately 6380 cm^2 cm^{-3}. The loss of organic matter in the sediments from dredging could also have an impact on the P kinetics. Previous work in ditches from this area have shown that the EPC$_o$ concentrations and P buffering capacity of sediments were more highly correlated to the organic matter present in the sediments than the silt and clay size fractions (Smith et al., 2005).

The dredging process also exposed gleyed materials, indicating the removal of Fe from the system or strong reducing conditions that would decrease the P sorption capacity of the newly exposed sediments (Ponnamperuma, 1972). This would also support the results of greater Mehlich-3 P with lower EPC$_o$ in the pre-dredged sediments than the dredged sediments. Mehlich 3–extractable Fe and Al concentrations from sediments were two and three times greater, respectively, in the pre-dredged sediments than the dredged sediments (Table 2). This resulted in PSR values approximately 54% greater in the dredged sediments during the adsorption experiment ($P < 0.05$). This is an important finding, as in the benthic sediments, Fe and Al are the cations controlling P solubility. As such, reducing the concentration of these elements during dredging resulted in changing the physiochemical parameters governing P transport such that PSR and EPC$_o$ were increased.

Additionally, the presence of living organisms in the sediments can influence rates of P uptake and release in aquatic habitats (Horne and Goldman, 1994; Barko and James, 1998). Dredging results in removal of sediments and biomass within sediments, and newly uncovered sediments typically contain different abundances, diversity, and species composition of organisms than the removed sediments (Koel and Stevenson, 2002). Therefore, changes in living organisms in the sediment as a result of dredging may also influence rates of P uptake and release in the sediments. When water column P concentrations are low, submerged macrophytes can utilize P from the benthic sediments (Barko and Smart, 1980). Macrophytes may also release O$_2$ through their root systems into sediments, thereby creating conditions for oxidation of Fe, which can then remove labile P from the water column (Stephen et al., 1997).

The kinetic parameters of P removal from the water column by the sediments are presented in Table 3. The α and β parameters were greater for the pre-dredged sediments than the dredged sediments for the adsorption experiment. This data verifies that sediment adsorption of P was greater in finer-textured pre-dredged sediments than dredged sediment. Examining the correlation co-efficients when this equation is fit to data from both replications indicates a strong relationship. The instantaneous rate of change in concentration at time 0 was $-14\,\mu M$ P h^{-1} for the pre-dredged sediments and $-9\,\mu M$ P h^{-1} for the dredged sediments. These results concur with an experiment using a fluvarium to study P uptake by sediments in the United Kingdom, for which an uptake rate of 20 μM h^{-1} was reported (House et al., 1995). The estimated P concentration at equilibrium (C_∞) was numerically greater for the dredged sediments than the pre-dredged sediments (Table 3), however this effect was not significant. The actual P concentrations in the water column following the adsorption experiment were significantly greater in the dredged sediments ($P < 0.05$).

Results from the current study demonstrate the immediate potential impact of dredging on P transport in streams. The temporal extent to which these effects occur is not yet known, however the detrimental effects of dredging may be diminished after 3 mo (Macrae et al., 2003). Other studies that have shown potential benefits from dredging lake sediments, as a result of reduced internal loading, have also indicated that after 1 yr, fluxes from pre-dredged sediments are similar to fluxes from sediments exposed after dredging (Kleeberg and Kohl, 1999).

Desorption Experiment

Water column P concentrations in the initial samples taken during the desorption experiment were between 0.003 and 0.006 mM, although P-free water was used to replace the high-P water from the adsorption phase. Similar observations have been made in other studies of fluvial P transport (McDowell and Sharpley, 2003). The most likely reason for this was the mixing of interstitial water with high levels of P water from the sediments with the P-free water added to the reservoirs of the fluvarium.

Mean water column P concentrations from the desorption experiment were greater for the dredged treatment than the pre-dredged treatment ($P < 0.001$; Fig. 2). While the rate of P removal was greater for the pre-dredged sediments during the adsorption experiment, the rate of release to "clean" water was lower for these sediments during the desorption experiment. These data would suggest that sediments present in the ditch before dredging were able to remove P into more stable complexes than sediment exposed in the ditch after dredging. At the end of 24 h, water column P concentrations were lower in the pre-dredged sediments ($P < 0.05$; 0.006 and 0.010 mM P for pre-dredged and dredged sediment treatments, respectively).

Table 3. Kinetic parameters from P adsorption and desorption experiments of stream simulations for pre-dredged and dredged sediments.

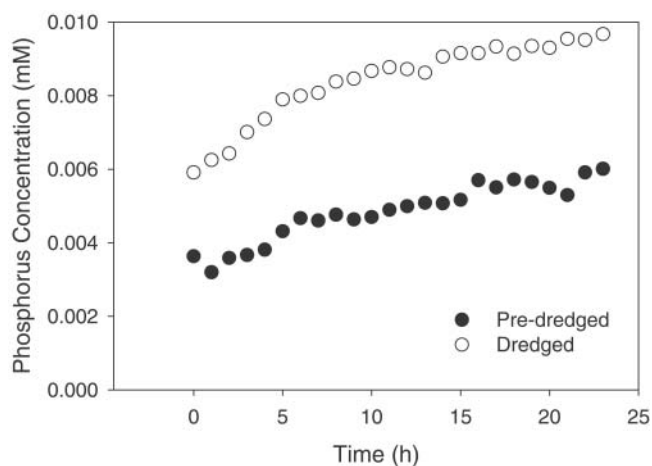| Treatment	C_∞	C_o	α	β	R^2	Final P concentration	dC/dt at $t = 0$
	mM					mM	μM h^{-1}
Adsorption							
Pre-dredged	0.0870	0.55	0.435	0.0371	0.99	0.075	−14.3
Dredged	0.0946	0.55	0.392	0.0240	0.85	0.111	−8.8
Desorption							
Pre-dredged	0.0067	0.0033	0.0034	0.0609	0.27	0.006	+0.205
Dredged	0.0097	0.0058	0.0039	0.125	0.44	0.010	+0.488

Fig. 2. Mean phosphorus concentration in a desorption experiment following approximately 6 d of P loading for pre-dredged and dredged sediments.

As with sediments from the adsorption experiment, the Mehlich-3 P in the pre-dredged sediments was greater than the dredged sediments (Table 2). Mehlich-3 P values in this experiment were also greater in the desorption experiment than the adsorption experiment by 30 to 40 mg kg^{-1}, indicating that P had been adsorbed by the sediments during the adsorption experiment. Interestingly, EPC$_o$ values for the pre-dredged sediments were relatively unchanged from the adsorption to desorption experiment, while there was a reduction in EPC$_o$ values for the dredged sediments for samples taken from the desorption experiment compared to samples collected during the adsorption experiment (Table 2). Values for PSR were greater during the desorption experiment than the adsorption experiment, primarily due to increased levels of P in the sediments. As with the adsorption experiment, pre-dredged sediment PSR values were lower [$P < 0.001$; 0.08 mmol P (mmol^{-1} [Al + Fe])] than PSR from dredged sediments [0.15 mmol P (mmol^{-1} [Al + Fe])].

Strong correlation coefficients resulted when the desorption data from each replication were fit to Eq. [2] (R^2 = between 0.73 and 0.97), however when data from both replications were used, variability was large enough that the regression equations were not as strong (R^2 = 0.27 and 0.43 for pre-dredged and dredged sediments respectively; Table 3). The initial rate of release of P from the sediments to the water from the dredged sediments was more than twice that observed for the pre-dredged sediments.

When water column P concentrations are low, labile P from benthic sediments can be released to the water, buffering the water column P levels. From the data collected during this experiment, it appears that sediments collected after dredging release P to the water column quicker than sediments present before dredging. This is supported by the greater β values, which were approximately two times greater for the dredged sediments than pre-dredged sediments (0.125 and 0.061, respectively; Table 3). Furthermore, dredged sediments appear to buffer water column P at concentrations greater than those

observed for sediments taken before dredging. The potential to deliver greater masses of P to downstream reservoirs could produce negative environmental impacts, including accelerated eutrophication, and concomitant reduction in drinking water quality.

Hysteresis was apparent, as C_∞ values were roughly an order of magnitude greater in the adsorption phase than desorption phase (Table 3). Interestingly, the values for the first-order rate constant (β), calculated from desorption phase data, were two to five times greater than the β values for the adsorption phase. This observation is a result of P in sediments and water being nearer the calculated equilibrium at 24 h during the desorption phase.

CONCLUSIONS

Ditch dredging is a frequent practice to ensure adequate removal of water from agricultural fields in the midwestern United States. However, this practice may alter the downstream delivery of anthropogenic contaminants. Removal of P from a water column loaded with approximately 0.55 mM P was greater in pre-dredged sediments than dredged sediments. Additionally, P concentrations after several days were greater in the dredged sediments than pre-dredged sediments. The desorption experiments found that the release of P to the water column occurred quicker and to a greater extent from dredged sediments than pre-dredged sediment, with final P concentrations in the water column after 24 h of 0.006 mM for pre-dredged and 0.010 mM for dredged sediment treatments.

Data from this experiment indicate that water quality may be impaired immediately after dredging, as the exposed sediments buffer P at greater concentrations than the sediments present before dredging. The authors recognize the fact that periodic dredging of these ditches is essential to ensure adequate drainage of agricultural fields in the contributing area. Given this information, further research should be conducted to identify potential physical or chemical treatments to increase the P removal by dredged sediments, and decrease the concentration at which these sediments buffer water column P concentrations. Conservation managers should also consider these findings during their selection of dredging criteria. Further research should also be conducted to confirm these findings, to determine if other treatments could be used to increase the P sorption of dredged sediments, and to determine how long the potential effects last.

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